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BIOCYBERNETICS: AN INTERACTIVE MAN-MACHINE INTERFACE

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Project Summary

The research project described herein deals with the capability of training a human subject to control and/or interact with complex electronic or mechanical systems. Basically the project involves the detection of bioelectrical phenomena that are analogs of ongoing cognitive processes and the utilization of these phenomena to control external events. The project also allows the system being controlled to communicate with the human operator in either a feedback or an interactive manner. In bypassing the subject's manual or verbal response apparatus an appreciable time saving is achieved. By eliminating the normal feedback/interactive modes of communication currently employed by machines (generally visual signals produced mechanically or electronically) a further potential time saving is realized. However, the major advantage of the proposal is the virtually automatic control of systems operation by the trained subject.

Introduction

We are training subjects to respond to alpha-numeric symbols such that a discriminable response will be obtained to each symbol. The symbols are a truncated set of the English alphabet. The response is the electromyogram (EMG) recorded from the surface of the skin overlying muscle. The EMG is most directly an index of motor nerve activity rather than of muscle activity level since the magnitude of the electrical response is a direct function of the amount of neural activity imposed upon the individual motor units of skeletal muscle. The EMG is always present upon sufficient neural activity to elicit muscle movement and is also detectable given neural activity insufficient to generate movement. Interestingly, when a subject is instructed to "think about" flexing a specific muscle, a recording of the EMG accompanying this cognitive process is possible. In short, the EMG has the unusual property of being activated by the mere thought of activating the response system, e.g., the muscle (Leuba & Dunlap, 1951). This property of the EMG has been known for years (Hefferline & Perera, 1958) and has been utilized in several applied bioengineering situations, most notably the control of prosthetic devices. In this case, the subject, with sufficient training, becomes quite adept at controlling his prosthetic device and reaches the point where he need not actively conceptualize a muscle movement to produce the EMG signals necessary to control the limb and reach his goal, but merely "thinks" of the desired movement to be performed. The thought of the movement is sufficient to produce the necessary EMG's. Later in his training he need not even think of the movements necessary to reach the goal, but merely thinks of the goal with the same lack of direct, conscious commands as does an intact human. It follows, of course, that the muscles used to control the limb cannot be occupied with other tasks that would produce error commands.

Our project deals with the capability of training a human subject to control and/or interact with complex electronic or mechanical systems. Basically the project involves the detection of bioelectrical phenomena that are analogs of ongoing cognitive processes and the utilization of these phenomena to control external events. The project also allows the system being controlled to communicate with the human operator in either a feedback or an interactive manner. In bypassing the subject's manual or verbal response apparatus an appreciable time saving is achieved. By eliminating the normal feedback/interactive modes of communication currently employed by machines (generally visual signals produced mechanically or electronically) a further potential time saving is realized.

The first year objectives were twofold: 1) to develop the interactive systems hardware and software, and 2) to train subjects to generate and respond correctly to alpha-numeric symbols using EMG responses. The first annual progress report detailed these accomplishments.

A central instrument in the conduct of this project is the augmented PDP-12 computer configuration. Since we have completed the transition from off-line logic control to on-line control and analysis, we are now in a position from the computational point of view to be able to acquire up to 24 simultaneous EMG and EEG records as necessary to support the various tasks. This acquisition capability in conjunction with the data storage and computational capability in the form of the disc facility and the floating point processor provide a highly flexible tool for use in the accomplishment of the defined task sequences.

The software which was developed before delivery of the addon equipment was oriented toward the control of the training program. We are currently expanding these software sets to utilize the full capabilities of the system.

Subjects have been trained to generate 16 different muscle patterns on cue. The process of training subjects to generate these precisely defined motor responses to visual stimuli proceeds from a simple match-to-sample task to the codification of a truncated alphabet by these defined sets of responses. The responses currently being directly trained are the electromyographic (EMG) records from the skin surface overlying four muscles:

Left and right flexor pollicis brevis (thumbs),

Left and right obductor digiti minimi (little fingers).

Subjects are required to generate these EMG responses without appreciable movements of the muscles or fingers. This aspect of the task -- generating the EMG's -- has proved easy for subjects and surprisingly "enjoyable" for them. They report that it is "fun" to do it with the attendant computer biofeedback. We have emphasized use of immediate visual feedback in training to date. It is in fact remarkable how quickly untrained subjects can learn the task. We were pleasantly surprised that training naive subjects proceeds so fast. We have a strong impression that the manual capabilities of man, utilized in terms of EMG activity rather than substantial movements, far exceed expectations based on current manual task requirements.

Current Project Status

The funding support upon which this project is predicated was not received until May, 1973. During the five months between the starting date of the second year and the receipt of funds, the University of California at Irvine loaned us a small sum of money which allowed us to continue the project at a minimal support level. The restricted support necessitated the selection of a subset of the second year's goals to be pursued. Consequently the major effort during the past six months has been directed to two projects. The first was a study of the significance of biological feedback in performance acquisition. Secondly, effort was directed toward developing computer programs capable of handling the segmentation problem associated with a subject's generating multiple sequential characters.

I. Biofeedback

This study employed two groups, one with maximal feedback (i.e., visual, auditory and reinforcement signals); the second with only reinforcement signals denoting successful matching of the R code to the S code. A replication currently in progress, will assess the relative contribution made by auditory and visual feedback in acquisition of a performance. It is clear that this feedback enhances problem solving but a distinction must be made between problem solving and performance acquisition. The intent here is to validate training procedures aimed at improving performance.

General Procedures. Subjects were trained to generate 16 different muscle patterns on cue. The process of training subjects to generate these precisely defined motor responses to visual stimuli proceeded from a simple match-to sample task to the codification of a truncated alphabet by use of these defined sets of responses. The responses trained were the electromyographic (EMG) records from the skin surface overlying four muscles:

Left and right flexor pollicis brevis (thumbs),

Left and right obductor digiti minimi (little fingers).

Subjects were required to generate these EMG responses without appreciable movements of the muscles or fingers. The four muscles permit 16 combinations of response/no response patterns. Testing and training took place in a sound-attenuating, ventilated chamber which was dimly lit (see Figure 1). The subjects sat in a comfortable, stuffed chair and were not required to utilize any of their musculature to remain in a comfortable position. Subjects faced a window in the room through which they saw the lamp display and alphanumeric display devices (to be described later). A black cloth around these units reduced distracting visual stimuli to a minimum. The EMG was recorded using gold disc electrodes and electrode paste and held on with tape.

Patterned Light Training. Each of the 16 EMG combinations was assigned a particular alphanumeric code (see Appendix A). These codes can be considered as four lamps which can be lit or dark in various combinations. Thus, to train subjects we employed a lamp display panel (see Figure 2). The display consists of two rows of incandescent lamps. Lamps in the top row have orange lenses, the lamps on the bottom are green and the single lamps on the extreme right and left are red.

Rather than initially present the alphanumeric display and the associated code as displayed on the lamp display we first trained the subjects to respond to the lamps alone. It was felt that this was a somewhat simpler task and that the alphanumeric display training would represent the second phase of the study. The task consisted of the presentation of a pattern of lit lamps on the upper row. The upper row of lamps for convenience are referred to as the S code (Stimulus Code) lamps. The subject was to turn on the lower row of lamps such that the pattern of lit lamps in the two rows coincided. The lower row of lamps will be referred to as the R Code (Response Code) lamps. Thus, the task is a match-to-sample paradigm.

Every 6-10 seconds the S Code was displayed for 1.5 seconds. At the same time the left hand red lamp was lit signalling the start of a trial (termed the GO lamp). The subject then issued a response. If successful in matching to the sample the right hand red light was lit (reinforcement lamp). At the end of the trial the lamp display panel was turned off.

Response Recording and Encoding. The previously described muscles were mapped on the surface of the overlying skin to determine the location yielding the best signal to noise level. Using differential amplification the most satisfactory results were obtained by placing the active electrode over the belly of the muscle and the indifferent over the distal tendon. All recording configurations employed earlobe grounding. Amplifier gain was from 30-150 V/cm. (Grass polygraph--EEG channel) with a bandpass of 1 to 75 Hz. The four channels of EMG information were amplified and simultaneously written onto a pen-writing polygraph. The amplified EMG was fed to a series of voltage comparators which produced a standard logic level pulse when the voltage of the EMG exceeded a selected level. The PDP-12 computer's external sense lines then permitted decoding of the logic level R Codes under software control. As a function of the detected R Code and at the experimenter's option the computer 1) activated the R Code lamps for patterned visual feedback; 2) activated audio oscillators which are spatially arranged for auditory feedback; or 3) displayed the R Code alphabetic character on the alphanumeric display unit as a form of cognitive feedback.

The S Code presented on any trial was randomly determined by a high-speed digital clock that transferred its count to the S Code flip-flops upon command from a timer. The flip-flops in turn activated the lamp drivers and S Code lamps of the display panel. The computer interpreted the S Code and monitored the sense lines for the subject's R Code. While monitoring and matching the R Code to the S Code, the computer constantly updated the feedback options with the current R Code responses. When a match was detected between the S Code and R Code the computer signaled a reinforcement. This program provided a letter by letter analysis for each trial consisting of an indication of the S Code, the subject's response, and the latency for each muscle group in milliseconds.

The paradigm followed consisted of four consecutive daily sessions with 256 trials of patterned light training and then four more consecutive daily sessions with 256 trials of alphabetic training with no patterned lights, either S or R Codes. Between the patterned light and letter training, the subjects were given the alphanumerics and their codes to learn. Appendix B has the instructions which the subjects read prior to the first session. While being presented the S codes, one group of eight subjects (feedback) received the following feedback modes informing them of the specific EMG's generated:

1) R Code lamp illumination;

2) Audible tones, spacially arranged relative to the EMG's involved;

3) A reinforcement lamp illumination when the R Code matched the S Code.

The second group of subjects (non-feedback) received only the reinforcement lamp illumination to inform them of the correctness of their EMG generations.

Results. The data obtained from the two groups of biofeedback subjects was subjected to an error analysis. The error analyses were of two types, referred to as Measure A and Measure B, both of which express a conditional probability of error. Method A is that given an error has occurred, what are the probabilities of eliciting an error by each of the stimulus codes. The measure is thus the intersection of the overall probability of error and the individual stimulus eliciting the error. A large number indicates a higher propensity to issue incorrect responses to that particular stimulus. The data from the feedback (F) and non-feedback (NF) groups are analyzed by Method A for each alphanumeric character as a function of type of training (Light Training and Letter Training) as a function days. Column probability of error scores [P(e)] are included to assess improvement with practice.

Table 1 presents the results of Measure A to the respective alphanumerics. The left hand column of Table 1 lists the associated binary codes. These binary codes can be related to EMG activation of particular musculature by referring to Table 2. An inspection of the daily error scores [P(c)] within a treatment condition across days shows that a significant improvement occurred across days within each treatment. This data has been graphically presented in Figure 3. From this figure it is apparent that in addition to an effect of days there is an effect of feedback. The feedback group both starts at a lower error level and improves to a final level which is superior to the non-feedback group. It is clear that the presence of feedback in this task clearly improves acquisition performance.

It is of considerable interest to note that the data plotted for the light training and letter training is a repeated measure on the same groups of subjects. The day one error scores are similar for the letter training phase and the light training phase of the experiment. The end training values on days 4 are also similar. This observation suggests that skills learned under light training have little transfer value to letter training. An alternative interpretation is that without the initial light training the letter training learning curves would show a greater number of initial errors. We cannot rule this possibility out as it was not specifically tested. However, it appears that the initial assumptions regarding training protocols in this project wherein we assumed that there would be considerable transfer from patterned light training to letter training may be in error. It now seems reasonable to consider bypassing the initial patterned light training which would result in an appreciable reduction in training time.

The data of Table 1 were ranked from stimuli eliciting the least errors to stimuli eliciting the most errors for each treatment condition across days. Table 3 presents the ranking of conditional probability of error for light training and Table 4 presents the rankings for letter training. It can be seen that the relative positions of the light patterns/letters remain generally stable across days. The overall number of errors drops as a function of practice but the relative distribution of error eliciting stimuli remains generally fixed. Thus, these data were collapsed across days into the data of Table 5 which gives the mean rankings over days.

From Table 5 it can be seen that those stimuli eliciting the least errors are characterized by a relatively simple response configuration. The binary codes 0000 and 1111 are uniformly superior to more complicated patterns. On the other hand, the stimuli eliciting the most errors are those codes requiring a complex bilateral response, for example 1101. There are several interesting inconsistencies in the error-response patterns whose explanation is not immediately apparent. These are typified by the codes 0011(S) and 0001(I). These data are of interest both theoretically in relation to cerebral dominance and interaction and practically in that they identify "error prone" stimuli. We now can proceed to restructure the alphanumeric code assignments to minimize error signals to high probability alphanumerics. For example, the letter "E", which is the most frequently appearing letter in English usage occupies an error position halfway down the range. We propose to structure the new code assignments such that they will be at the intersection of the 1) letter frequency, 2) information content of the letter, and 3) the "error quotient" of the code. By using such an approach we can reduce the deleterious effects of error signals to a minimal and acceptable level.

The second type of error analysis performed on this data (Method B) expresses the conditional probability of an error type. Given that an error has occurred to any stimulus, what are the probabilities of the type of error in terms of the alphanumeric code. A large number indicates a higher propensity to produce an error having this particular code. In other words, when an error occurs what pattern does it have.

Table 6 presents the results of considering the error types for all treatments across days. The column error percentages are the same as those indicated in Table 1 as the data are identical, only the method of analysis differs. A cursory inspection of Table 6 indicates that by far the most common error is to activate all the EMG channels, 1111(D). For ease of interpretation these data are expressed in a ranking in Table 7 (Light Training) and Table 8 (Letter Training). The relative ranking positions of error type can be seen to change in a complex manner as a function of training. An overall condensation of the data is presented in Figure 9 showing the error ranking across days. The most common error signal is an activation of all EMG channels. These data will be utilized in the construction of the new EMG alphanumeric codes discussed above.

The biofeedback study we have just reported on has given us a good deal of information regarding the training protocols which are an essential component of this project. The results of the biofeedback study indicate the value of feedback in the acquisition of the task and point out the general value of specific feedback information on motor/conceptual tasks. We now seriously question the necessity for the patterned light training procedure employed heretofore. Although we cannot be certain of the value of such preliminary training without experimental verification it appears as if high levels of subject performance can be achieved rapidly without such pretraining. The present results clearly indicate the necessity to restructure the EMG alphanumeric code assignments. We propose to create a code system which takes into account the relative letter frequency, information content and "error quotient" of the code. Such a new code assignment should reduce error signals to a negligible and, thus, acceptable level.

II. Sequential Response Support

We have proceeded with the software support necessary to implement the sequential responding nature of the project. The task is to give subjects the opportunity to "spell" words using their EMG response apparatus. The words will be "spelled" either in response to alpha-numeric display (a match-to-sample task) or in an open-end response mode of responding. In both cases the subject generated code will be displayed providing immediate visual reinforcement. In one case, visual/auditory cueing, the subject is required to match-to-sample, and is a form of machine-to-man communication. In the other case, subject initiated words, the communication takes the form of man-to-machine.

There are several rather subtle issues to be considered at this point. While the mere training of subjects to "spell" words on command or by initiation may seem somewhat simplistic, consider for a moment what is actually occurring and how it differs from forms of motor skill training.

1) We are having subjects encode an arbitrarily defined set of responses. We have, for convenience only, assigned alpha-numeric values to these sets of responses; there is no intrinsic reason why these response sets could not just as well be defined as functional commands to control man-machine systems.

2) We are dealing with 16 or 32 response patterns. There is no intrinsic reason why, using these procedures, the maximum number of unique codes could not be expanded to 512 or 1024. At this stage of understanding it is more fruitful to reduce complexity rather than expand complexity.

3) A major milestone in this phase will be the development of a sequencing algorithm for deciding under program control when to advance from acquiring R codes as one letter or command to acquiring these R codes as another letter or command. This is a significant issue in that subjects do not generate all responses at precisely the same instant in time. Hence, some time period must be allowed for the generation of all responses necessary for a particular letter or code. The issue to be resolved during this phase is whether a predefined time window or "capture timer" is sufficient for the sequencing at this time, or if we must engage in mathematical sequencing algorithms similar to the sequencing in linguistic analysis.

We have completed the development of the software support for the sequential response problem (program designation = Δ res). The program has been tested using a capture time of 250 msec which ensures a 90-95% accuracy in well trained subjects. We are currently integrating this system with a device to detect small concurrent movements of the response associated fingers. This latter device is essentially a control device which will feed an error signal or null into the computer. This system will perform two functions. First, it will form the basis for a gross movement error detector and second, it will provide a sensitive means of eliminating the tendency to respond overtly. Upon integration of the sequential response program and the movement detector we will decrease the capture times window to determine the minimal effective sequential response times.

References

Hefferline, R. F., & Perera, T. B. Proprioceptive discrimination of a covert operant without its observation by the subject. Science, 1963, 139, 834-385.

Leuba, C., & Dunlap, R. Conditioning imagery. J. exp. Psychol., 1951, 41, 352-355.

Appendix A

Below are the S Codes and their corresponding alphanumerics. The codes were devised with the following considerations in mind. First it was thought to be desirable to give the most commonly occurring alphabetic characters the simplest code. Thus, the letter E received a simple code: the right brevis alone. Since we have 15 codes to issue we determined the 15 most frequent letters and tested them for intelligibility. The 15 letters below comprise a high percentage of those letters actually used in normal communication and can convey a good deal of information.

The codes are given octal representation merely as a convenience.

Alphabetic Character	Left Minimi 4	Left Brevis 3	Right Brevis 2	Right Minimi 1	Binary Code	Octal Code
E			X		0010	02
A		X			0100	04
I				X	0001	01
N	X				1000	10
O		X	X		0110	06
R	X	X			1100	14
S			X	X	0011	03
T	X			X	1001	11
L		X		X	0101	05
C	X		X		1010	12
U		X	X	X	0111	07
P	X		X	X	1011	13
M	X	X		X	1101	15
H	X	X	X		1110	16
D	X	X	X	X	1111	17

The Xs indicate which of the lamps are to be lit for a given alphabetic character.

APPENDIX B

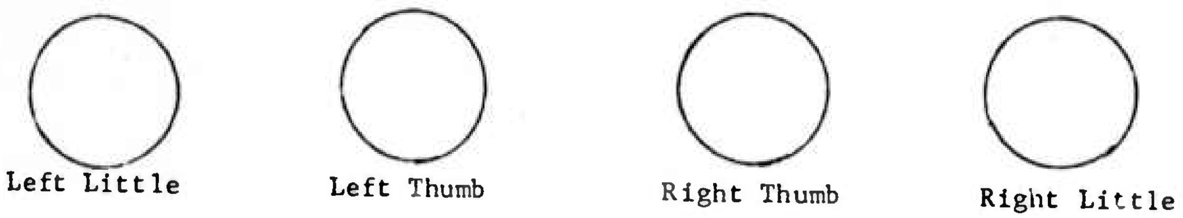
ARPA Instructions to Subjects

This is a study of human performance. We are interested in ways to improve human performance. You will be given various signals, each of which calls for a specific response from you. You will make many wrong responses at first, but your performance will improve with the number of trials. Don't worry about making a wrong response -- they are useful to us too, but try your best to make the right one.

The signal will consist of a pattern of lights which are arranged in a horizontal row. There is a total of four lights, and the pattern may consist of any combination of lights from "all off" to "all on".

Your response will consist of a movement of your thumbs and 4th fingers on both hands either one at a time or in various combinations. This movement causes a change in the electrical potential of the activated muscle. We can monitor and record this change of potential as an electromyogram (EMG). This is done by placing a surface electrode on the skin immediately overlying the activated muscle. (This involves no pins or clamps -- the electrode merely lies flat on the skin). There is no shock involved. With this electrode system we can only record -- not stimulate. When you make a response, we will monitor the EMG only -- we are not interested in the actual, overt movement. If you can generate a potential of adequate magnitude without a large amount of movement -- by all means, do so.

Assignment of Fingers and Lights. Basically, the experiment works like this: When one or more of the four top, yellow, lights is lit, it is a signal for you to move the muscle which has been assigned to that light. The assignments are as follows:



Place your open hands palms down on the armrests of the chair. The lights and muscles are in the same sequence horizontally.

As different combinations of lights flash on, try to match them with the appropriate combination of movements. Your response should come as soon as possible after the lights appear. A new trial will be given every 6-10 seconds, and there will be a total of 256 trials per day. A run will last about one hour. (Errors): You can make two types of errors in your response: 1) you can fail to match with an EMG a light which is lit; 2) you can make a muscle-response which is not called for -- that is, the corresponding light is not lit.

In both cases you will fail to see the square red light on the right side of the panel light up. This light is only turned on by a correct response. When you see it lit up after a trial, you know that you have made the desired response. <u>Please try to get accuracy first, and speed second</u>.

LEGENDS

Figure 1 - Physical arrangement of the training facilities.

Figure 2 - Representation of the interactive display devices. The subject is seated one meter in front of the devices.

Figure 3 - The probability of generating an error, as a function of training condition (light training or letter training), feedback or non-feedback, and days.

Table 1 - Conditional probability of error - Measure A. Raw data expressed for all treatments and days.

Table 2 - Binary Code to EMG response.

Table 3 - Ranking of conditional probability of error - Measure A. Light training as a function of feedback/non-feedback and days.

Table 4 - Ranking of conditional probability of error - Measure A. Letter training as a function of feedback/non-feedback and days.

Table 5 - Ranking of conditional probability of error - Measure A. Light and letter training for feedback/non-feedback collapsed across days.

Table 6 - Conditional probability of error - Measure B. Raw data expressed for all treatments and days.

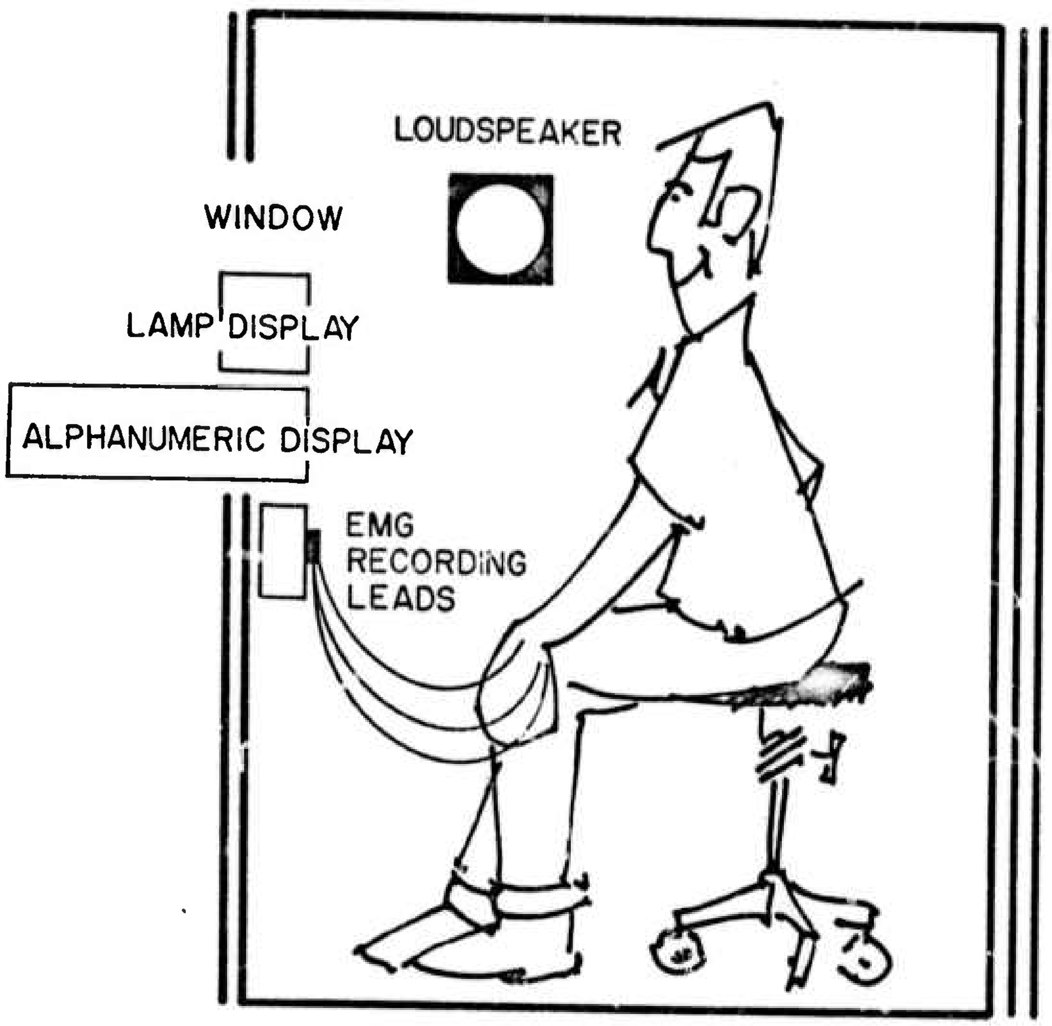
Table 7 - Ranking of conditional probability of error - Measure B. Light training as a function of feedback/non-feedback days.

Table 8 - Ranking of conditional probability of error - Measure B. Letter training as a function of feedback/non-feedback and days.

Table 9 - Ranking of conditional probability of error - Measure B. Light and letter training for feedback/non-feedback collapsed across days.

FIG. 1

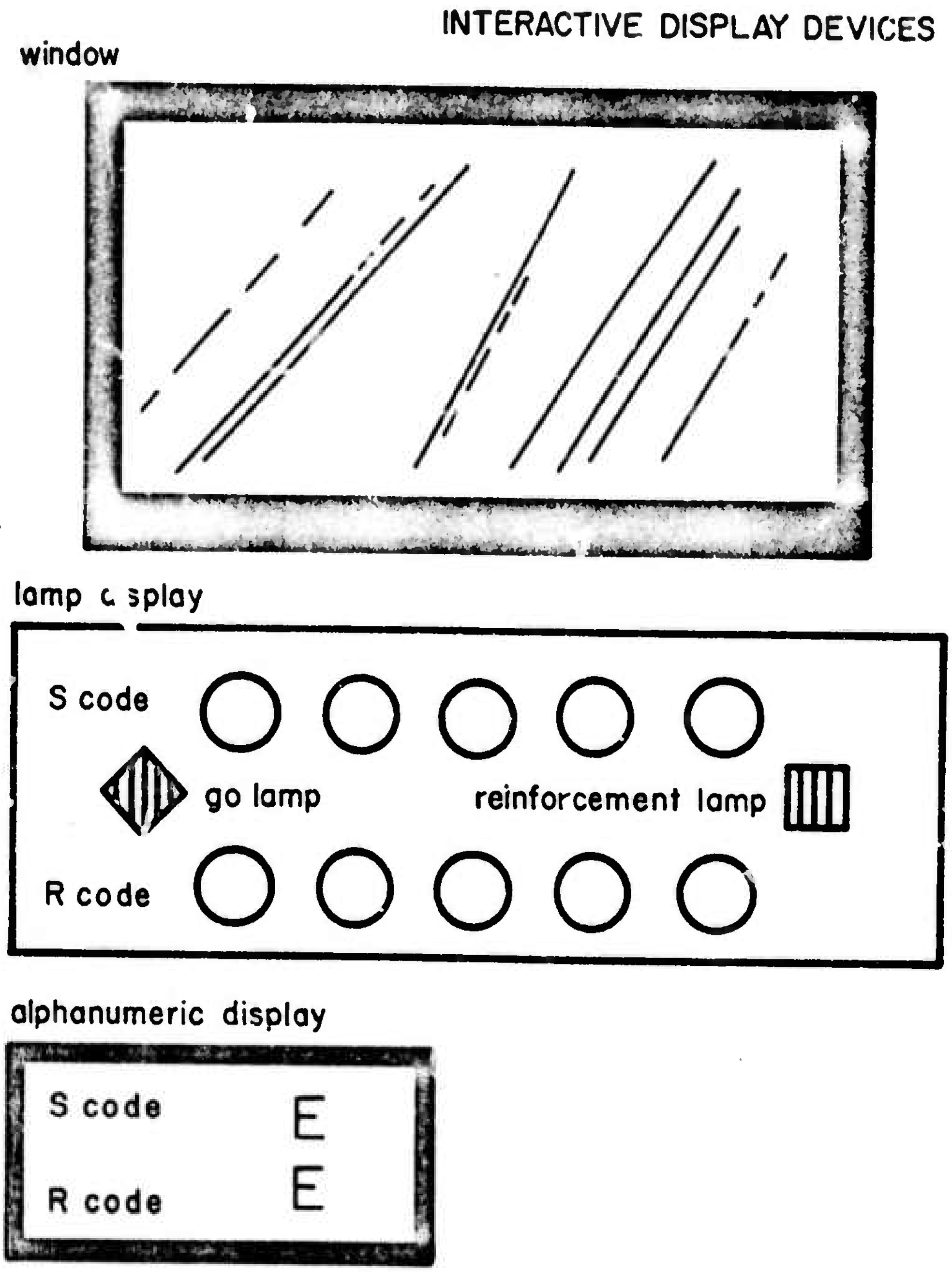
PHYSICAL ARRANGEMENT



SOUND ATTENUATING ROOM

PHYSICAL ARRANGEMENT OF TRAINING FACILITIES

FIG. 2


INTERACTIVE DISPLAY DEVICES
window
lamp display
S code
go lamp
reinforcement lamp
R code
alphanumeric display
S code
E
R code
E

91

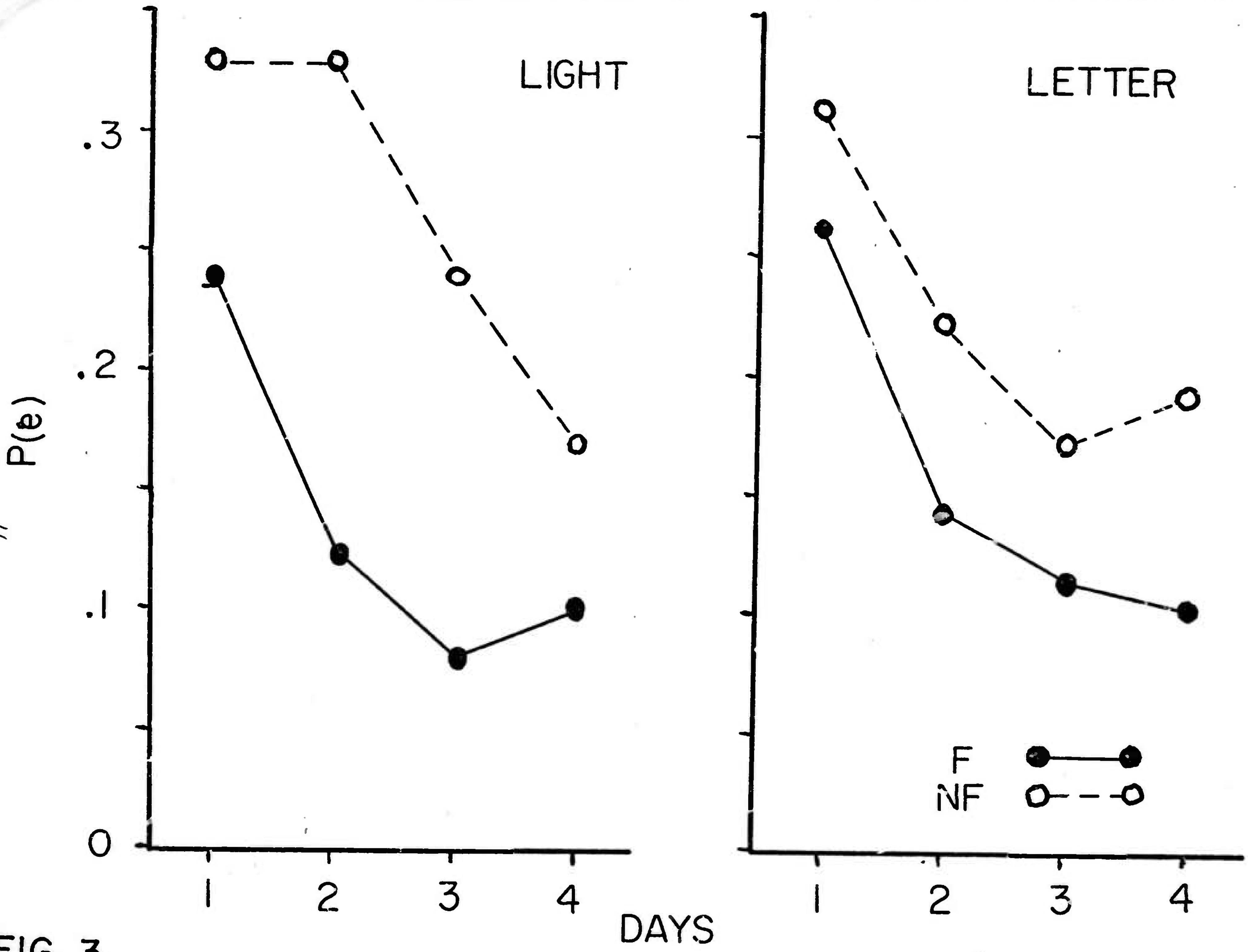


FIG. 3

TABLE 1

BIOFEEDBACK - CONDITIONAL PROBABILITY OF ERROR - MEASURE A

		Light Training								Letter Training							
		Day 1		Day 2		Day 3		Day 4		Day 1		Day 2		Day 3		Day 4	
Binary Code	Alphanumeric	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF
0000	(Blank)	.02	.02	.04	.01	.02	.01	.03	.02	.01	.003	.02	.004	.02	.01	.01	.007
0100	A	.07	.06	.06	.06	.09	.03	.07	.05	.03	04	.08	.03	.05	.07	.06	.09
1010	C	.08	.07	.11	.09	.07	.04	.06	.10	.07	.09	.06	.07	.06	.11	.09	.09
1111	D	.02	.03	.00	.03	.00	.04	.004	.07	.03	.02	.01	.02	.03	.01	.01	.02
0010	E	.06	.05	.05	.07	.07	.06	.06	.04	.04	.06	.08	.04	.02	.04	.04	.03
1110	H	.05	.06	.02	.05	.10	.05	.01	.10	.07	.08	.09	.11	.08	.09	.04	.08
0001	I	.07	.19	.04	.19	.09	.27	.14	.05	.06	.03	.03	.05	.04	.04	.04	.02
0101	L	.07	.08	.08	.08	.08	.11	.09	.08	.08	.06	.06	.07	.06	.06	.06	.07
1101	M	.09	.09	.12	.06	.10	.08	.08	.10	.13	.11	.17	.08	.15	.11	.13	.11
1000	N	.04	.03	.03	.05	.03	.05	.04	.02	.07	.04	.04	.05	.04	.05	.05	.03
0110	O	.05	.04	.08	.08	.03	.05	.02	.08	.05	.07	.04	.08	.08	.04	.08	.08
1011	P	.08	.07	.13	.08	.10	.05	.02	.08	.11	.11	.10	.11	.12	.12	.12	.13
1100	R	.03	.03	.03	.02	.06	.01	.05	.04	.04	.05	.06	.03	.01	.03	.05	.03
0011	S	.03	.03	.08	.03	.02	.2	.07	.04	.03	.05	.02	.03	.06	.02	.04	.01
1001	T	.08	.06	.03	.04	.05	.04	.05	.05	.08	.06	.04	.08	.06	.05	.04	.08
0111	U	.05	.05	.03	.07	.02	.05	.06	.06	.04	.07	.04	.10	.08	.10	.04	.09
	P(e)	.24	.33	.12	.33	.08	.24	.10	.17	.26	.31	.14	.22	.11	.17	.10	.19

TABLE 2

BINARY CODE TO EMG

Binary Code = 0 0 0 0

LEFT	LEFT	RIGHT	RIGHT
Obductor	Flexor	Flexor	Obductor
Digiti	Pollicus	Pollicus	Digiti
Minimi	Brevis	Brevis	Minimi
(Little Finger)	(Thumb)	(Thumb)	(Little Finger)

TABLE 3

RANKING OF CONDITIONAL PROBABILITY OF ERROR - MEASURE A

LIGHT TRAINING

	Day 1		Day 2		Day 3		Day 4	
	F	NF	F	NF	F	NF	F	NF
Least Errors	(BL)0000	(BL)0000	(D)1111	(BL)0000	(D)1111	(BL)0000	(D)1111	(N)1000
↑	(D)1111	(D)1111	(H)1110	(R)1100	(BL)0000	(R)1100	(H)1110	(BL)0000
	(R)1100	(N)1000	(M)0111	(S)0011	(S)0011	(A)0100	(S)0011	(E)0010
	(S)0011	(R)1100	(T)1001	(D)1111	(U)0111	(C)1010	(P)1011	(R)1100
	(N)1000	(S)0011	(R)1100	(T)1001	(O)0110	(D)1111	(O)0110	(S)0011
	(U)0111	(O)0110	(N)1000	(N)1000	(N)1000	(T)1001	(BL)0000	(T)1001
	(O)0110	(E)0010	(BL)0000	(H)1110	(T)1001	(U)0111	(N)1000	(I)0001
	(H)1110	(U)0111	(I)0001	(A)0100	(R)1100	(P)1011	(T)1001	(A)0100
	(E)0010	(T)1001	(E)0010	(M)1101	(C)1010	(O)0110	(R)1100	(U)0111
	(A)0100	(H)1110	(A)0100	(U)0111	(E)0010	(N)1000	(C)1010	(D)1111
	(I)0001	(A)0100	(L)0101	(E)0010	(L)0101	(H)1110	(E)0010	(L)0101
	(L)0101	(C)1010	(O)0110	(L)0101	(A)0100	(E)0010	(U)0111	(O)0110
	(T)1001	(P)1011	(S)0011	(O)0110	(I)0001	(M)1101	(A)0100	(P)1011
	(P)1011	(L)0101	(C)1010	(P)1011	(P)1011	(L)0101	(M)1101	(C)1010
↓	(C)1010	(M)1101	(M)1101	(C)1010	(M)1101	(S)0011	(L)0101	(H)1110
Most Errors	(M)1101	(I)0001	(P)1011	(I)0001	(H)1110	(I)0001	(I)0001	(M)1101

TABLE 4

RANKING OF CONDITIONAL PROBABILITY OF ERROR - MEASURE A

LETTER TRAINING

	Day 1		Day 2		Day 3		Day 4	
	F	NF	F	NF	F	NF	F	NF
Least Errors	(BL)0000	(BL)0000	(D)1111	(BL)0000	(R)1100	(BL)0000	(BL)0000	(BL)0000
↑	(A)0100	(D)1111	(BL)0000	(D)1111	(BL)0000	(D)1111	(D)1111	(S)0011
	(D)1111	(I)0001	(S)0011	(S)0011	(E)0010	(S)0011	(U)0111	(I)0001
	(S)0011	(N)1000	(I)0001	(R)1100	(D)1111	(R)1100	(T)1001	(D)1111
	(U)0111	(A)0100	(U)0111	(A)0100	(N)1000	(O)0110	(S)0011	(E)0010
	(R)1100	(R)1100	(T)1001	(E)0010	(I)0001	(I)0001	(I)0001	(N)1000
	(E)0010	(S)0011	(O)0110	(N)1000	(A)0100	(E)0010	(H)1110	(R)1100
	(O)0110	(T)1001	(N)1000	(I)0001	(T)1001	(N)1000	(E)0010	(L)0101
	(I)0001	(L)0101	(R)1100	(L)0101	(S)0011	(T)1001	(N)1000	(H)1110
	(C)1010	(E)0010	(L)0101	(C)1010	(L)0101	(L)0101	(R)1100	(O)0110
	(H)1110	(O)0110	(C)1010	(M)1101	(C)1010	(A)0100	(L)0101	(T)1001
	(N)1000	(U)0111	(E)0010	(O)0110	(U)0111	(H)1110	(A)0100	(U)0111
	(T)1001	(H)1110	(A)0100	(T)1001	(O)0110	(U)0111	(O)0110	(C)1010
	(L)0101	(C)1010	(H)1110	(U)0111	(H)1110	(M)1101	(C)1010	(A)0100
↓	(P)1011	(P)1011	(P)1011	(P)1011	(P)1011	(C)1010	(P)1011	(M)1101
Most Errors	(M)1101	(M)1101	(M)1101	(H)1110	(M)1101	(P)1011	(M)1101	(P)1011

TABLE 5

RANKING OF CONDITIONAL PROBABILITY OF ERROR - MEASURE A

ACROSS DAYS

	Light Training F	Light Training NF	Letter Training F	Letter Training NF
Least Errors	(D)1111	(BL)0000	(BL)0000	(BL)0000
	(BL)0000	(R)1100	(D)1111	(D)1111
	(N)1000	(N)1000	(S)0011	(R)1100
	(S)0011	(D)1111	(R)1100	(I)0001
	(U)0111	(T)1001	(I)0001	(N)1000
	(R)1100	(A)0100	(E)0010	(E)0010
	(O)0110	(E)0010	(N)1000	(A)0100
	(H)1110	(U)0111	(U)0111	(L)0101
	(T)1001	(O)0110	(T)1001	(O)0110
	(A)0100	(H)1110	(A)0100	(T)1001
	(E)0010	(P)1011	(O)0110	(H)1110
	(C)1010	(S)0011	(L)0101	(C)1010
	(L)0101	(C)1010	(C)1010	(U)0111
	(P)1011	(L)0101	(H)1110	(M)1101
	(I)0001	(I)0001	(P)1011	(P)1011
Most Errors	(M)1101	(M)1101	(M)1101	(S)0011

BIOFEEDBACK - CONDITIONAL PROBABILITY OF ERROR - MEASURE B

		Light Training								Letter Training							
		Day 1		Day 2		Day 3		Day 4		Day 1		Day 2		Day 3		Day 4	
Binary Code	Alphanumeric	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF
0000	(Blank)	.020	.051	.015	.021	.028	.019	.021	.023	.090	.153	.030	.033	.026	.048	.029	.041
0100	A	.020	.033	.019	.034	.097	.021	.015	.039	.031	.031	.010	.013	.043	.017	.029	.028
1010	C	.040	.049	.031	.024	.080	.044	.026	.019	.079	.017	.074	.032	.052	.031	.083	.026
1111	D	.201	.210	.226	.250	.000	.328	.268	.264	.101	.147	.206	.314	.151	.294	.122	.247
0010	E	.038	.022	.015	.030	.074	.028	.015	.074	.064	.034	.030	.024	.112	.028	.059	.043
1110	H	.119	.098	.096	.097	.102	.060	.077	.070	.088	.131	.091	.088	.043	.126	.073	.099
0001	I	.008	.028	.038	.004	.091	.007	.026	.027	.028	.015	.020	.013	.034	.039	.034	.028
0101	L	.020	.025	.042	.012	.080	.016	.031	.016	.046	.023	.017	.031	.043	.017	.054	.038
1101	M	.056	.035	.084	.095	.102	.023	.046	.023	.059	.080	.051	088	.052	.076	.073	.041
1000	N	.032	.060	.015	.050	.034	.051	.052	.019	.044	.039	.030	.015	.034	.045	.044	.041
0110	O	.101	.082	.034	.038	.034	.053	.021	.112	.070	.062	.091	.073	.052	.056	.063	.066
1011	P	.078	.042	.065	.044	.102	.079	.072	.058	.037	.060	.088	.084	.151	.053	.078	.064
1100	R	.034	.082	.054	.100	.068	.056	.077	.050	.061	.049	.071	.086	.060	.062	.063	.043
0011	S	.080	.070	.061	.086	.023	.074	.119	.093	.057	.043	.074	.048	.065	.045	.117	.074
1001	T	.028	.041	.057	.040	.057	.063	.026	.008	.068	.023	.030	.015	.034	.025	.034	.020
0111	U	.123	.074	.146	.075	.028	.077	.108	.105	.077	.091	.084	.073	.047	.039	.049	.099

TABLE 7

RANKING OF PROBABILITY OF ERROR - MEASURE B

LIGHT TRAINING

	Day 1		Day 2		Day 3		Day 4	
	F	NF	F	NF	F	NF	F	NF
Least Common	(I)0001	(E)0010	(N)1000	(I)0001	(D)1111	(I)0001	(A)0100	(T)1001
	(L)0101	(L)0101	(E)0010	(L)0101	(S)0011	(L)0101	(E)0010	(L)0101
	(BL)0000	(I)0001	(BL)0000	(BL)0000	(U)0111	(BL)0000	(O)0110	(N)1000
	(A)0100	(A)0100	(A)0100	(C)1010	(BL)0000	(A)0100	(BL)0000	(C)1010
	(T)1001	(M)1101	(C)1010	(E)0010	(N)1000	(M)1101	(C)1010	(BL)0000
	(N)1000	(T)1001	(O)0110	(A)0100	(O)0110	(E)0010	(I)0001	(M)1101
	(R)1100	(P)1011	(I)0001	(O)0110	(T)1001	(C)1010	(T)1001	(I)0001
	(E)0010	(C)1010	(L)0101	(T)1001	(R)1100	(N)1000	(L)0101	(A)0100
	(C)1010	(BL)0000	(R)1100	(P)1011	(E)0010	(O)0110	(M)1101	(R)1100
	(M)1101	(N)1000	(T)1001	(N)1000	(C)1010	(R)1100	(N)1000	(P)1011
	(P)1011	(S)0011	(S)0011	(U)0111	(L)0101	(H)1110	(P)1011	(H)1110
	(S)0011	(U)0111	(P)1011	(S)0011	(I)0001	(T)1001	(R)1100	(E)0010
	(O)0110	(O)0110	(M)1101	(M)1101	(A)0100	(S)0011	(H)1110	(S)0011
	(H)1110	(R)1100	(H)1110	(H)1110	(P)1011	(U)0111	(U)0111	(U)0111
	(U)0111	(H)1110	(U)0111	(R)1100	(M)1101	(P)1011	(S)0011	(O)0110
Most Common	(D)1111	(D)1111	(D)1111	(D)1111	(H)1110	(D)1111	(D)1111	(D)1111

TABLE 8

RANKING OF PROBABILITY OF ERROR - MEASURE B

LETTER TRAINING

	Day 1 F	Day 1 NF	Day 2 F	Day 2 NF	Day 3 F	Day 3 NF	Day 4 F	Day 4 NF
Least Common	(I)0001	(I)0001	(A)0100	(C)1010	(BL)0000	(A)0100	(BL)0000	(T)1001
↑	(A)0100	(C)1010	(L)0101	(I)0001	(T)1001	(L)0101	(A)0100	(C)1010
	(P)1011	(L)0101	(I)0001	(A)0100	(N)1000	(T)1001	(T)1001	(I)0001
	(N)1000	(T)1001	(T)1001	(N)1000	(I)0001	(E)0010	(I)0001	(A)0100
	(L)0101	(A)0100	(N)1000	(T)1001	(A)0100	(C)1010	(N)1000	(L)0101
	(S)0011	(E)0010	(E)0010	(E)0010	(H)1110	(I)0001	(U)0111	(M)1101
	(M)1101	(N)1000	(BL)0000	(L)0101	(L)0101	(U)0111	(L)0101	(N)1000
	(R)1100	(S)0011	(M)1101	(BL)0000	(U)0111	(N)1000	(E)0010	(BL)0000
	(E)0010	(R)1100	(R)1100	(S)0011	(C)1010	(S)0011	(O)0110	(R)1100
	(T)1001	(P)1011	(S)0011	(O)0110	(M)1101	(BL)0000	(R)1100	(E)0010
	(O)0110	(O)0110	(C)1010	(U)0111	(O)0110	(P)1011	(H)1110	(P)1011
	(U)0111	(M)1101	(U)0111	(P)1011	(R)1100	(O)0110	(M)1101	(O)0110
	(C)1010	(U)0111	(P)1011	(R)1100	(S)0011	(R)1100	(P)1011	(S)0011
	(H)1110	(H)1110	(O)0110	(H)1110	(E)0010	(M)1101	(C)1010	(H)1110
↓	(BL)0000	(D)1111	(H)1110	(M)1101	(P)1011	(H)1110	(S)0011	(U)0111
Most Common	(D)1111	(BL)0000	(D)1111	(D)1111	(D)1111	(D)1111	(D)1111	(D)1111

TABLE 9

RANKING OF CONDITIONAL PROBABILITY OF ERROR - MEASURE B

ACROSS DAYS

	Light Training F	Light Training NF	Letter Training F	Letter Training NF
Least Common	(BL)0000	(I)0001	(A)0100	(C)1010
	(N)1000	(L)0101	(I)0001	(T)1001
	(E)0010	(BL)0000	(N)1000	(A)0100
	(A)0100	(A)0100	(L)0101	(I)0001
	(I)0001	(C)1010	(T)1001	(L)0101
	(T)1001	(E)0010	(BL)0000	(E)0010
	(L)0101	(T)1001	(M)1101	(N)1000
	(C)1010	(M)1101	(R)1100	(S)0011
	(O)0110	(N)1000	(U)0111	(R)1100
	(R)1100	(P)1011	(E)0010	(O)0110
	(S)0011	(O)0110	(O)0110	(P)1011
	(M)1101	(R)1100	(C)1010	(BL)0000
	(P)1011	(H)1110	(H)1110	(M)1101
	(H)1110	(S)0011	(S)0011	(U)0111
	(U)0111	(U)0111	(P)1011	(H)1110
Most Common	(D)1111	(D)1111	(D)1111	(D)1111